# SCANNING FOR VISUAL TRAFFIC: AN EYE TRACKING STUDY

Kurt Colvin[1], Rahul M. Dodhia[2,3], Sean Belcher[2,3] and Key Dismukes[3]
[1]Cal Poly, San Luis Obispo [2]San Jose State University [3]NASA Ames Research Center

The FAA and various safety organizations recommend a specific, systematic out the window (OTW) visual scanning pattern for pilots to see and avoid other aircraft. Little research has been published on how effectively pilots actually scan. In our study, pilots fly VFR scenarios in a general aviation flight training device (GAFTD) equipped with head and eye tracking equipment. This paper describes methods for analyzing eye-tracking data and presents preliminary results of pilots' OTW scanning performance.

## Introduction

Despite safety improvements in some areas of general aviation, midair collisions remain steady at around 0.035 per 100,000 flying hours, or about 15 per year (FAA, 1998a). According to FAR 91.113, the primary defense for a midair collision is the principle of "see and avoid." The FAA and other organizations recommend a timed, systematic, visual scan in which the pilot fixates at a location for at least one second, then shifts gaze no more than 10 degrees to the next sector in the visual field. Pilots are advised to look inside the cockpit no more than 4-5 seconds for every 16 seconds spent scanning the outside world (FAA, 1998b). Although all pilots are exposed to this concept, they do not receive systematic or extensive training in how to execute it. Little research has been published to reveal what scanning patterns pilots actually use or how effective those patterns might be.

Our ongoing study attempts to determine the patterns of scanning for visual traffic pilots use under varying levels of workload and traffic density. We have adapted a commercial eye tracking system that allows free head movement for use in a general aviation flight training device (GAFTD) with realistic cockpit displays and controls. Eye tracking systems that allow pilots to move their heads freely in flight simulators can provide powerful methods to explore issues of traffic scanning and cockpit monitoring (Wickens, Xu, Helleberg, Carbonari, & Marsh, 2000; Mumaw, Sarter & Wickens, 2001; Anders, 2001).

Two major challenges confront attempts to relate eye tracking data to visual scanning issues: (i) an enormous amount of data must be processed to track eye movements occurring several times per second, and (ii) pilots' scanning patterns presumably may vary substantially from moment to moment, making it difficult to determine and describe the constantly shifting patterns. For these reasons previous eye-tracking studies in simulated flight have relied mainly on percentage of time spent looking inside and outside the cockpit, however this measure does not provide information about scanning patterns and by itself does not allow us to ascertain whether a pilot would detect conflicting traffic before collision. We have developed a set of algorithms that allow scanning patterns to be partially characterized, and we are developing additional algorithms for more extensive characterization.

We are currently analyzing data from five pilots. To illustrate our approach this paper presents some of our preliminary data from two pilots.

## Methods

### *Eye and Head Tracking*

Eye tracking data were collected using the ISCAN, Inc. Line Of Sight (LOS) system. This equipment consists of a headband fitted with a camera to determine the eye position and a magnetic sensor to determine head orientation. Information from these sensors is input to a PC (The "ISCAN PC") equipped with ISCAN hardware, which, in conjunction with ISCAN software, does the computations necessary to determine where the pilot is looking in the cockpit.

To facilitate analysis, the cockpit was divided into seven two-dimensional planes, referred to as the areas of interest (AOIs). Four of these AOIs were the GAFTD's windscreens displaying the "outside" visual world, two of the planes were instrument and engine indicator panels, and the remaining plane was the clipboard on the yoke, where the pilot had standard checklists to perform during the flight (see Figure 1). The LOS system calculates the plane to which gaze is directed, the location of gaze within the plane (X and Y coordinates), and pupil diameter of the eye. These parameters are sampled at a rate of 60 Hz.

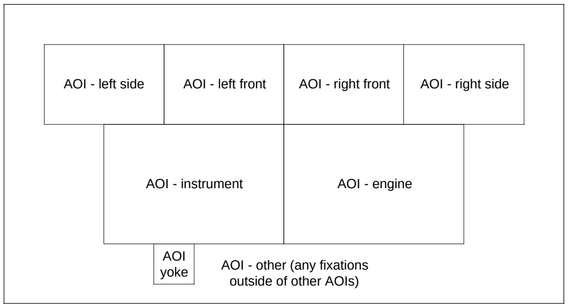


Figure 1. Two-dimensional map of GAFTD AOIs. The side displays are actually tilted to correspond to the side windows of a cockpit.

### *Data Collection*

The three parameters specifying the pilot's gaze (AOI, X and Y coordinates) were output from the ISCAN PC over a common serial cable to another PC (The "Data Collection PC"). Additionally, on a second serial port, six real time simulator parameters (altitude, latitude, longitude, airspeed, heading and simulator elapsed time) were input to the Data Collection PC. An application was written in LabVIEW to enable this PC to integrate and synchronize the data from the two sources. Timestamp, event and traffic acknowledgement information from the flight scenario was added to the data stream, which was then recorded to a disk file. Altogether, thirteen parameters were recorded at a frequency of 60 Hz.

### *Experimental Task Description*

Five participants have been run to date. All possessed at least a current FAA instrument rating with appropriate airplane ratings and had 20/20 vision or were corrected to that value. The median of flight hours was 1400 and the median years flying was 15. An AST Hawk 201 FAA-approved flight training device was used to simulate a high performance, complex single engine piston aircraft. Participants were given written instructions, flew a scripted 45-minute training session to familiarize them with the GAFTD, and were then calibrated on the eye tracking apparatus.

Participants then flew the experimental scenario, a 45-minute VFR cross-country flight in which they navigated by VORs on a flight plan without interacting with ATC. Identification of the navigation facilities were modified and a flight route map were chosen to disguise the part of the country in which the flight occurred so that participants would not know what traffic density to expect. After reaching cruise altitude, participants encountered in sequence a low workload period (3 minutes), a high workload period created by moderate turbulence in the vicinity of high terrain (3 minutes), a second low workload period (3 minutes), a traffic period (14 minutes), and a final low workload period. During the traffic period aircraft appeared OTW for periods ranging from 43 to 75 seconds at various crossing angles. Nine aircraft appeared, one at a time, with 30 seconds between. The aircraft were traveling level at either 500 feet or 1000 feet above or below the participants' aircraft, however it was not initially obvious that the aircraft were not on a collision course. All participants received the same traffic presentations.

### *Data Analysis*

The first step in processing the raw data was to determine the duration and position of each eye fixation, which was done by what is known as the absolute deviation method (Salvucci & Goldberg, 2000). The absolute deviation of a cluster of data points is calculated by summing the horizontal and vertical range distances. If the absolute deviation of a successive sequence of points is within a defined limit (approximately 1 degree visual angle), and the duration of that sequence is above another defined threshold (100 ms), then that cluster of points is defined as a fixation. (These deviation and duration values are commonly used in eye-tracking research, however they can be modified for future analysis). This fixation analysis provides four parameters—mean horizontal and vertical location, duration and AOI—that are used by our algorithms for calculating spatial and temporal patterns of eye movements.

We report here two of the methods we are using to analyze scanning patterns. To analyze spatial aspects we calculate a transition probability matrix, which describes the probabilities of moving gaze from its current AOI to each of the other AOIs. This measure specifies the direction of transition between pairs of AOIs, as well the probability (Ellis, 1986). For temporal aspects we calculate "lag time", which is the interval starting when gaze departs a particular AOI and ending gaze returns to that AOI. This measure helps address the question of whether pilots check each OTW sector frequently enough to detect an aircraft on a conflicting path before a collision would occur. For the purpose of illustration in this paper, we provide only data about transition probabilities and lags among AOIs, although our data allow us to also examine transitions and lags within AOIs. We also present data about the percent of time participants spent gazing at each AOI.

## Results

We are currently analyzing the data from the five participants. For illustration we present here preliminary data from participants 4 and 5 in which the three low workload periods are combined.

Table 1 shows the percentage distribution of gaze time among the AOIs and the lag distributions, defined as the mean time between successive fixations within each AOI. The two participants differed markedly in distributing their gaze inside and outside the cockpit. Participant four's distribution of gaze time was 32% on navigation/engine instruments and 61% on the four OTW displays, whereas the distribution for participant five was 68% inside and 31% outside. Both participants spend the preponderance of OTW time gazing at the left front display directly in front of the pilot's seat. Mean lag time distributions generally mirrored gaze time distributions. The mean lag times for the left front display were 1.7 seconds for participant four and 4.7 seconds for participant five. Lag times were much greater for other AOIs, especially the right side display, for which the mean lags were 24.5 and 48.5 seconds, respectively. The range of lag times was large for some AOIs, especially the right side display, for which the maximum lags were 80.0 and 120.0 seconds, respectively.

Table 2 shows the probability of transition of gaze from an AOI on the left side of the table to each of the other AOIs shown in the columns. Regularities can be seen in the transitions of both participants. The most common transition from the left front display was to the navigation instruments and vice versa. The most common transition from the right front display was to the left front display for participant four, but for participant five the transition probability from right front was distributed rather evenly over several AOIs. For both participants, the transition from the left side display was predominantly to the left front display. However, despite these regularities, the occurrence of multiple transition paths from most AOIs indicates that scan pattern varied considerably over time.

We performed a preliminary analysis of the effects of increasing workload (data not shown) and found that the two participants responded differently. Transition patterns and lag distributions changed significantly for participant four ($p < 0.01$ by a Poisson log-linear regression) but did not change for participant five. Under higher workload, participant four scanned the side displays less often and concentrated more on the center displays and the instrument panel. This change may reflect his concern with maintaining airspeed, heading, and altitude during turbulence.

## Discussion

The main purpose of this paper is to illustrate the potential of eye-tracking techniques for studying pilots' monitoring performance. However, these preliminary results are in themselves revealing. Although both participants had substantial experience as general aviation pilots, their scanning performance differed substantially. One participant spent most of his time looking inside the cockpit, and increasing workload narrowed his visual scan. In contrast, the other participant spent most of his time looking outside the cockpit and did not let workload alter his scan. In comparison, Wickens and colleagues (2000), found that pilots in a GAFTD spent about 37% of their time attending to the outside world.

Distribution of gaze time between the cockpit and the outside world is not an adequate measure of pilots' scanning performance. The crucial issue is whether pilots look at each sector of the outside world frequently enough to detect conflicting traffic in time to avoid a collision. How often each sector must be scanned is a function of both aircrafts' airspeed and the collision geometry. Rate of closure is faster as the geometry approaches head-on collision, thus it is appropriate to scan forward somewhat more frequently. The FAA does not specify how frequently pilots should check each sector, but pilots following the FAA guidance would probably check each sector every 25-50 seconds.

Consider a light aircraft travelling at 140 knots on a right-angle collision course with a large aircraft travelling 200 knots (Figure 2). When these aircraft are 6.1 miles apart they will collide in 90 seconds. At six miles a large aircraft subtends a visual angle of about 0.015 degrees, and in this example the large aircraft is 55 degrees to the right of the light aircraft and would appear in the right side display of our GAFTD. We know of little data on how far away pilots can reliably detect an aircraft when scanning the appropriate sector. Data from Harris (1973) suggest that pilots would have an 86% chance of detecting a DC-3 six miles distant if fixating the target. Visual acquisition data from Andrews (1977) also suggest that six miles is a reasonable estimate of the range at which pilots might reliably detect an aircraft.

Would the scan patterns of our two participants enable them to detect the conflicting aircraft in this example? We developed the "lag" metric to characterize the mean time pilots' gaze is diverted from each AOI. Both of our participants scanned the left front display frequently enough to detect conflicting traffic with plenty of time to avoid a collision. However they scanned other OTW displays much less frequently.

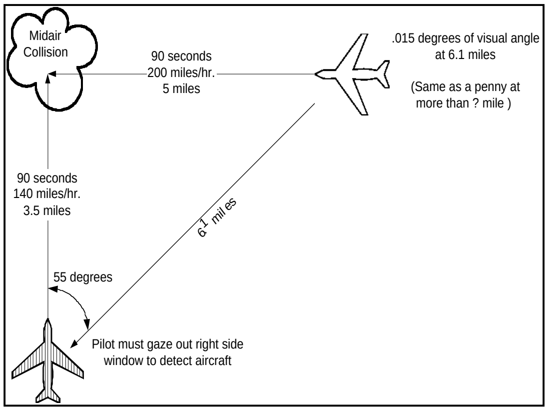


Figure 2. Possible collision scenario

Least frequently scanned was the right side display. The mean lag times for the right side display show that the scan patterns of both participants would have enabled them to detect this particular conflict before collision in most instances. However, the range of lag times is as important as the mean, and the range of lags for OTW displays other than front left is quite large. Some of participant 5's scan sweeps to the right side display took longer than the 90 seconds available before collision in this example. Also, if we assume that around 12 seconds is required from the time a pilot detects a target to execute an appropriate response (FAA, 1998b), in some instances participant 4 would not have been able to avoid this collision.

The FAA recommends that pilots scan OTW systematically, moving gaze from one sector to the next in a regular pattern. Even with eye-tracking measurement, it is difficult to characterize pilots' visual scanning because eye movements vary substantially from moment to moment, even when individuals attempt to be systematic. We developed the transition probability matrix as a partial measure of the spatial characteristics of scanning. Our data show some regularities, especially in moving gaze back and forth between the left front display and the navigation instruments, however, scanning was also highly variable. A highly regular scan pattern would show up as transitions from each AOI being predominantly to one other AOI, e.g., left side-->left front-->right front-->right side. Our data show transitions from most AOIs to be distributed to several other AOIs, indicating that participants did not consistently follow a single scan pattern throughout the nine minute period. However it is possible that participants engaged in a systematic scanning pattern for one period and then switched to another systematic scanning pattern for another period. We are currently developing more sophisticated algorithms to analyze for shifting scan patterns. Also we will analyze scanning at the level of 10 degree sectors (Our current OTW AOIs range from 15 to 20 degrees, depending on their slant to a line from the pilot's head).

Do pilots scan in our GAFTD the same way they do in real aircraft? We don't know the answer to this question, although we did instruct them to do so. In future experiments we will use instructions to manipulate the importance participants attach to visual scanning.

Scanning for visual traffic is a special case of the larger issue of monitoring. Sumwalt, Thomas, & Dismukes (2002) have pointed out that monitoring is an essential defense against threats to flight safety. Although several airlines have begun to increase emphasis on effective monitoring, we are hampered by lack of data. Mumaw et al. (2001) demonstrated the value of eye tracking to evaluate pilots' monitoring of cockpit automation indicators. The techniques we are developing for analyzing data could substantially enhance the power of eye tracking to study pilots' performance in many types of monitoring task.


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| AOI | Lag time distribution (seconds) | | | | | % gaze time |
|---|---|---|---|---|---|---|
| | mean | std dev | min | max | n | |
| Left Side | 10.8 | 14.5 | 0.5 | 81.0 | 45 | 2 |
| Left Front | 1.7 | 1.3 | 0.2 | 10.0 | 215 | 42 |
| Right Front | 10.6 | 17.0 | 0.3 | 68.0 | 41 | 6 |
| Right Side | 24.5 | 10.0 | 16.0 | 80.0 | 14 | 11 |
| Instruments | 2.3 | 1.9 | 0.1 | 11.0 | 173 | 26 |
| Engine | 16.9 | 16.8 | 0.4 | 58.0 | 17 | 6 |
| Other | 4.5 | 5.2 | 0.3 | 38.0 | 104 | 8 |

(a)

| AOI | Lag time distribution (seconds) | | | | | % gaze time |
|---|---|---|---|---|---|---|
| | mean | std dev | min | max | n | |
| Left Side | 21.6 | 18.4 | 0.5 | 48.0 | 15 | 3 |
| Left Front | 4.7 | 4.1 | 0.5 | 27.0 | 88 | 24 |
| Right Front | 21.8 | 12.5 | 0.9 | 41.0 | 19 | 2 |
| Right Side | 48.5 | 24.1 | 0.5 | 120.0 | 4 | 1 |
| Instruments | 2.3 | 1.3 | 0.2 | 6.0 | 86 | 65 |
| Engine | 49.3 | 31.7 | 6.2 | 92.0 | 6 | 3 |
| Other | 13.5 | 12.3 | 0.6 | 41.0 | 31 | 3 |

(b)

Table 1. Participant 4 (a) and Participant 5 (b).
Lag distributions for each AOI in the low workload condition, *n* (number of lags in the distribution), and *% gaze time* (percentage of time recorded as fixation spent in that AOI). The *Other* row corresponds to eye fixations not made in any of the AOIs. These two participants did not look at the yoke AOI.

| | Left Side | Left Front | Right Front | Right Side | Instruments | Engine | Other |
|---|---|---|---|---|---|---|---|
| Left Side | 0 | 77 | 3 | 0 | 17 | 0 | 1 |
| Left Front | 18 | 0 | 14 | 1 | 56 | 2 | 9 |
| Right Front | 1 | 52 | 0 | 15 | 16 | 1 | 14 |
| Right Side | 0 | 7 | 35 | 0 | 13 | 15 | 30 |
| Instruments | 3 | 54 | 2 | 1 | 0 | 4 | 37 |
| Engine | 0 | 9 | 0 | 3 | 27 | 0 | 61 |
| Other | 2 | 60 | 2 | 5 | 27 | 4 | 0 |

(a)

| | Left Side | Left Front | Right Front | Right Side | Instruments | Engine | Other |
|---|---|---|---|---|---|---|---|
| Left Side | 0 | 65 | 0 | 0 | 22 | 0 | 12 |
| Left Front | 16 | 0 | 22 | 0 | 52 | 1 | 9 |
| Right Front | 0 | 25 | 0 | 21 | 24 | 5 | 25 |
| Right Side | 0 | 33 | 22 | 0 | 0 | 11 | 33 |
| Instruments | 3 | 80 | 0 | 0 | 0 | 4 | 12 |
| Engine | 0 | 0 | 0 | 0 | 53 | 0 | 47 |
| Other | 3 | 3 | 3 | 5 | 80 | 6 | 0 |

(b)

Table 2. Participant 4 (a) and Participant 5 (b).
Transition probabilities of the form Pr (column | row) in the low workload condition, given as percentages. The *Other* row and column corresponds to eye fixations not made in any of the AOIs.